Pinniped Hearing in Complex Acoustic Environments

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LONG-TERM GOALS

Pinnipeds (seals, sea lions, and walruses) are amphibious marine mammals that are susceptible to coastal anthropogenic noise. The long-term goals of this effort are to improve understanding of (1) the sound detection capabilities of several pinniped species, and (2) the effects of noise exposure on the sound detection capabilities of these species. The research will show how amphibious mammals receive and perceive acoustic information in background noise.

OBJECTIVES

Improve understanding of hearing in pinnipeds by extending psychoacoustic profiles of sound reception obtained from simplified auditory processing tasks to those describing performance under increasingly complex acoustic conditions. Relate laboratory measurements to concurrent field studies of communication in fluctuating natural noise backgrounds. Strengthen predictive models that describe how signal structure and noise environments interact to constrain auditory performance, and develop weighting functions that can be used for species-typical acoustic risk assessments.

APPROACH

Psychoacoustic measurements of hearing are obtained from California sea lions, harbor seals, and northern elephant seals under highly controlled laboratory conditions. Long-term captive subjects are trained using operant conditioning procedures to report the presence or absence of auditory signals in noisy or quiet backgrounds. Testing takes place both under water (in a mapped, reverberant acoustic field) and in air (in a sound-attenuating hemi-anechoic chamber) because the sensitivity and frequency range of hearing in pinnipeds varies significantly as a function of medium. The stimuli presented during testing comprise synthetic and natural sounds that are systematically varied in spectral complexity, or in referential meaning established through explicit associative learning paradigms. The general approach is to obtain absolute detection thresholds for specific complex sounds and compare these thresholds to those previously obtained for pure-tone signals. The tasks are then repeated against a variety of synthetic and natural background masking stimuli to determine the signal-to-noise ratios that limit auditory detection, and in some cases, auditory recognition. The methods are modeled in

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part from studies of bird communication in noise (Dooling et al., 2009; Lohr et al., 2003) and build upon previous research in our laboratory on hearing capabilities and cognitive processing of auditory-visual information.

In addition to using psychoacoustic methods to assess auditory thresholds under varying signal and noise conditions, the metric of reaction time as a proxy for perceptual loudness measurements is investigated by measuring response latency while varying both signal frequency and signal level in acoustic detection tasks. The resultant latency-intensity functions are used to develop frequency-dependent equal latency contours. Equal latency countours should approximate equal loudness countours across the frequency range of hearing (Moody, 1970), and thus may be used to inform the development of accurate auditory weighting functions for pinnipeds.

Field measurements of representative species-typical vocalizations and associated ambient noise are made at pinniped breeding rookeries, and simple propagation models of natural signals through representative environments are generated. The data collected include physical measurements of environmental noise (maximum and equivalent continuous sound pressure level over different time scales) and vocalization parameters (source level, spectral composition, call duration, intercall interval). These data are combined with information about individuals (age, sex, identity, size, reproductive state, dominance status, and spatial movements) so that functional communication can be assessed through field experiments. Collectively, the complementary laboratory and field studies allow effective detection and recognition ranges for biologically relevant sounds to be modeled under various conditions of natural and anthropogenic noise.

Key personnel in the laboratory in FY2011 included the PI, research technician Asila Ghoul, UC Santa Cruz graduate students Jillian Vitacco (Ocean Sciences) and Peter Cook (Psychology), and marine mammal trainer Caroline Casey. Additional specific support to the laboratory experiments was provided by research assistants Arial Brewer, William Hughes, and Jenna Lofstrom. The field data were collected by the PI, Caroline Casey, and Dr. Brandon Southall, a collaborator from SEA, Inc. who is also a UC Santa Cruz Research Associate. The entire research program was supported by a team of 12-15 undergraduate and post-graduate volunteers and interns who receive formal training in marine mammalogy and bioacoustic research in exchange for their participation in the program.

WORK COMPLETED

In FY2011, significant accomplishments included (1) underwater audiometric testing of a young California sea lion that will participate in upcoming planned studies of auditory masking, (2) continuation of research on presbycusis with seals and sea lions, (3) completion of the psychoacoustic equal latency study with a harbor seal and California sea lion, (4) testing of low-frequency signal processing by harbor seals, and (5) completion of field measurements and field experiments on acoustic communication in northern elephant seals. A more detailed description of work completed follows.

(1) A young female California sea lion (NOA0006602) that was added to the permanent group of research animals housed in the laboratory in FY2010 completed training for participation in acoustic signal detection procedures and completed fine-scale testing of underwater auditory thresholds from 400 Hz to 36 kHz, including the entire range of best sensitivity.

(2) The other resident research animals, including a 26-year-old California sea lion, a 23-year-old harbor seal, and an 18-year-old northern elephant seal, participated in ongoing hearing testing as part of the monitoring effort for changes in hearing sensitivity as a result of experimental noise exposure and natural aging.

(3) The study of response latency as a proxy for loudness perception that was initiated in FY2010 was completed with two animals. The subjects were trained to depress an electronic switch and to release it immediately upon detection of an auditory stimulus. Repeated-measures testing for the adult harbor seal was completed at 7 frequencies across the aerial frequency range of hearing with 7-8 stimulus levels tested for each frequency (ranging from +0 dB to +40 dB above best sensitivity at each frequency). Repeated-measures testing for the adult California sea lion was completed at 7 frequencies with 6-7 stimulus levels tested for each frequency (ranging from +0 dB to +30 dB above best sensitivity at each frequency). The resultant latency-intensity functions obtained for each animal at each frequency were fit with an appropriate power function to generate equal latency contours.

(4) Due to the recent publication of a significant study on temporal processing of acoustic signals by seals (Kastelein et al., 2010), we obtained new data to directly test the hypothesis that seals may show unusually long integration times for low-frequency auditory signals. We tested a harbor seal listening for 200 Hz tones of either 500 ms or 2500 ms in a highly controlled acoustic chamber to determine if the differences reported by Kastelein et al. (2010) would be observed. To do this, high-resolution thresholds were obtained and reaction times were measured and compared for the two test conditions.

(5) Field studies of elephant seal communication in natural noise were conducted from at Año Nuevo State Park in San Mateo County, California during the winter breeding season. Comprehensive observations of acoustic signaling, behavioral interactions, physical characteristics, and spatial movement patterns were obtained from individually identified individuals, with a focus on subadult and adult males. Dyadic behavioral interactions were scored for dominance ranking determined by ELO ratings. A long-term study on source level characteristics was completed during FY2011 as well as data collection for analysis of individual variability among breeding males. These data were used to evaluate the extent of plasticity in vocal signals and to test the hypothesis that vocalizations are honest indicators of resource holding potential in this species. A series of field playback experiments were conducted using calls recoded from individuals of known size, rank, and familiarity directed toward dominant or subordinate associates in order to determine whether associative learning of vocalizations can explain how elephant seals use the information contained in acoustic signals to avoid costly fights.

RESULTS

(1) The underwater audiograms for the young California sea lion are provided in Figure 1. The close correspondence between the two individuals with presumably normal hearing tested in our laboratory are consistent with a revised analysis (Reichmuth and Southall, 2010) of earlier data obtained with this species (Schusterman et al., 1972), and can be considered the most representative species-typical hearing data currently available for otariid pinnipeds (sea lions and fur seals).

(2) Information on presbycusis, or age-related hearing loss, is rare for long-lived mammals including marine mammals and provides insight into likely hearing demographics within a species or functional hearing group. Data obtained through periodic testing of a California sea lion over a ten-year period is provided in Figure 2, and shows substantial hearing loss across the frequency range of hearing. Hearing loss appears earliest and is greatest in the high frequency portion of the audiogram (>10 kHz).

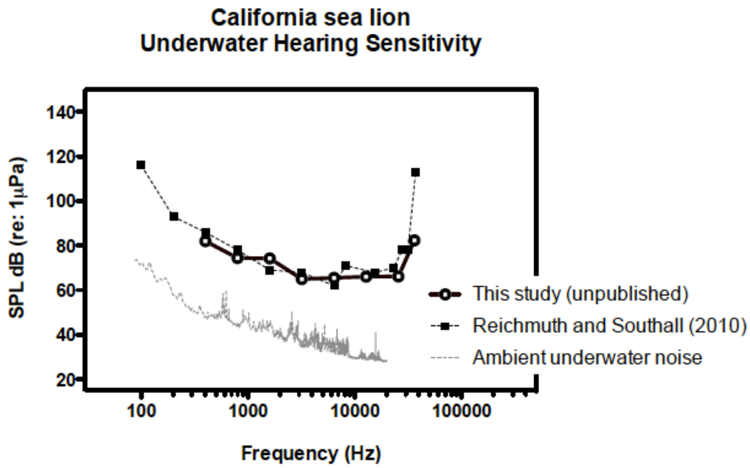

Figure 1. Underwater audiogram describing frequency specific hearing sensitivity for a three year old California sea lion as compared to the same data reported for an adult California sea lion with normal hearing. These are fine-scale hearing thresholds with low varability of 1.0-2.4 dB. Both data sets were obtained in the same quiet environment, described by the ambient noise curve shown in the figure.

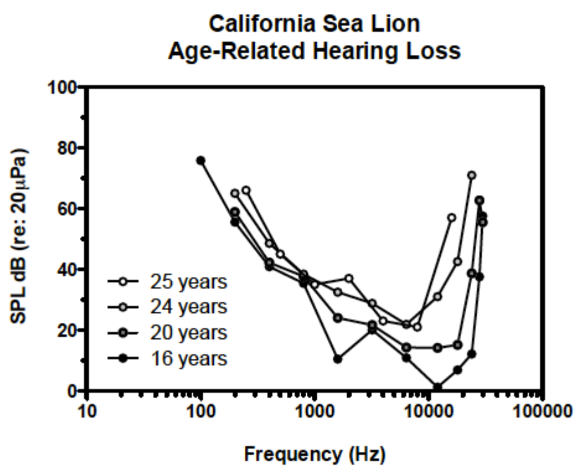

Figure 2. Presbycusis in an adult California sea lion as shown by change in aerial hearing thresholds measured over a 10 year period using similar methods. High-frequency hearing declined earliest and most rapidly. The same relative differences are both expected and observed in this individual's underwater hearing thresholds.

(3) The frequency-specific latency-intensity (L-I) functions that were measured for two subjects were used to produce the equal latency contours shown in Figure 3. The L-I functions were reliably fit by non-linear regression analysis using a power function, and the curve fit was then used to extrapolate sound pressure levels corresponding to discrete latency values for each subject. The equal latency contours are expected to reflect equivalent perceptual loudness of similar sounds of different

frequencies as has been shown for some primates. The data obtained show that that reaction times can be reliably measured and behave predictably as signal amplitude changes. The “M-weightings” currently used for mitigation and regulatory purposes are likely to be conservative, however, ongoing analyses will show how these new data can be applied to refine species-specific weighting functions.

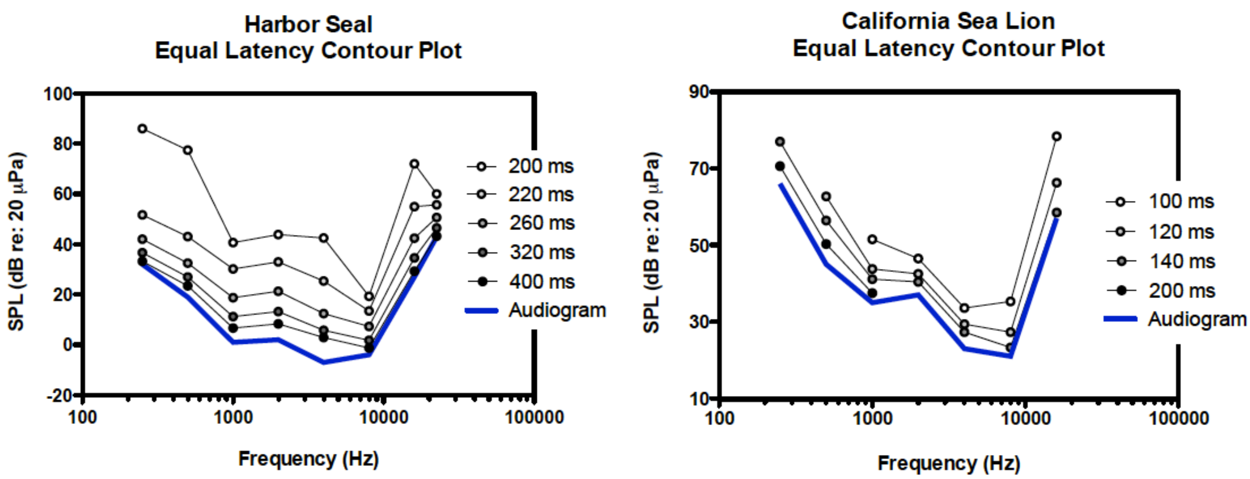

Figure 4. (left) Equal latency contour plot for an adult harbor seal with normal hearing derived from frequency specific latency-intensity functions. The isobars repesenting equivalent reaction times with respect to received sound pressure level are shown relative to the audiogram. (right) The same data shown for an adult California sea lion with age-related hearing loss.

(4) The data we obtained on low-frequency temporal processing of tones by a harbor seal do not support the report by Kastelein et al. (2010) which state that integration times for harbor seals exceed 3000 ms for 200 Hz tonal signals. This claim is significant as it implies that currently available hearing data for this species (and possibly others) would greatly underestimate the audibility of certain low-frequency sounds. The results from Kastelein et al. (2010) would predict a difference of 9 dB between thresholds measured for 200 Hz tones with duration of 500 ms or 2500 ms, however, we found no difference in measured hearing thresholds at these durations for a harbor seal tested in air (30.0 dB vs. 29.9 dB, with 95% confidence limits of 28.9-31.0 and 28.8-30.6 dB respectively).

(5) Multiple high quality acoustic measurements and recordings were obtained from over 40 breeding male elephant seals in FY2011. The intense, pulatile threat calls of males were individually recognizable, and had mean source levels of 108.2 +3.9 dB re: 20µPa with respect to rms levels and 126.5+3.2 dB re:20 µPa with respect to peak pressure levels. These extremely loud calls were used by signalers to displace subordinate individuals and by receivers to assess the dominance status of callers. An analysis of spectral and temporal call features did not support the hypothesis that these vocalizations were honest indicators of resource holding potential. However, the information contained in these signals was effectively recognized and used differentially by receivers as shown in field playback experiments, which did support an associative learning hypothesis. Planned additional analyses will determine the likelihood of informational masking by high levels of natural noise. The

collaborators on this effort are Nicolas Mathevon from the Universite de Saint-Etienne (Laboratory of Neuroethology) and Isabelle Charrier from the Université Paris Sud (Center for Neurosciences).

IMPACT/APPLICATIONS

The audiometric data generated by this project and preceding projects have contributed to noise exposure criteria developed specifically for free-ranging marine mammals, which in turn are used by the operational Navy, industry, and U.S. and International regulators to establish appropriate guidelines and mitigation for anthropogenic noise emissions in marine environments.

RELATED PROJECTS

An Opportunistic Study of Hearing in Sea Otters (Enhydra lutris): Measurement of Auditory Detection Thresholds for Tonal and Industry Sounds. C. Reichmuth (University of California Santa Cruz) is the PI; the project is supported by Minerals Management Service. This project expands upon auditory research with pinnipeds by examining hearing in another marine carnivore, the sea otter. There is overlap in facilities, experimental resources, and personnel.

Airgun Effects on Arctic Seals: Auditory Detection, Masking, and Temporary Threshold Shift. C. Reichmuth (University of California Santa Cruz) is the PI; the project is supported by the Joint Industry Programme on Sound and Marine Life. This project expands upon auditory research with pinnipeds by examining hearing and the effects of noise in arctic seals. There is overlap in facilities, experimental resources, and personnel.

Detection and Tracking of Submerged Hydrodynamic Wakes Using a Bioinspired Hybrid Fluid Motion Sensor Array. B. Calhoun (University of Virginia) is the PI; the project is supported by the Office of Naval Research (N00014-09-10468). Field testing of sensor design is conducted at Long Marine Laboratory with one of the seals involved in the current project. There is overlap in facilities, experimental resources, and personnel.

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